Attitude control for the Pluto Fast Flyby spacecraft

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Abstract

A conceptual attitude control subsystem design for the Pluto Fast Flyby spacecraft is described. Mass, cost, schedule and performance, approximately in that order, drove the mission, spacecraft, as well as the attitude control subsystem design. The paper discusses the key mission requirements impacting the attitude control subsystem design, a.. well as the important subsystem trades. The spacecraft is a three axis stabilized vehicle using cold gas jets for attitude control and hydrazine thrusters for trajectory correction maneuvers. Attitude determination relies heavily on a low mass star tracker capable of determining attitude by pointing anywhere in the celestial sphere. Tracking of planetary features with the star tracker may also be desirable. A small Inertial Reference Unit and a sun sensor will accompany the tracker to complete the suite of components for attitude determination.

1 INTRODUCTION

The conceptual design of the attitude control subsystem for the Pluto Fast Flyby spacecraft is described. This design is a result of a continuing study at Jet Propulsion laboratory on a very small spacecraft (under 150 kg) for a mission to Pluto, the one planet in the solar system yet to be explored by robotic spacecraft. Of various studies that have, been done for spacecraft to fly past l'lute, this marks the most complete study yet for a spacecraft solely dedicated to a flyby of that planet. Two spacecraft, each with internal hardware redundancy, are to complete fast flybys of Pluto and its moon Charon following direct trajectories from Earth. The science instruments include visible, infrared and ultraviolet imaging devices (visible imaging is intended to provide 1 km global resolution), as well as a radio science device to be used near the time of Earth occultation. The year following each flyby will be used to download most of the data gathered during the planetary encounter. The mission for each spacecraft is expected to last under 10 years.

In section 2 we give a description of the Pluto-Charon system, followed in section 3 by a brief discussion of past Pluto flyby studies. Section 4 discusses the mission scenario and mission constraints, and Section 5 briefly covers the spacecraft itself. The attitude control requirements and design are covered in Section

6 and the attitude determination function is discussed in Section 7. Hardware requirements and some of the algorithms needed for attitude control software are touched 011 in Section 8. Concluding remarks are made in Sec tion 9.

2 THE PLUTO-CHA RON SYSTEM

Pluto is normally the planet farthest from the sun during its 248 year orbit, but since 1979 it has been inside the orbit of Neptune, reaching perihelion in 1989. By 1999 it will once again be the outermost planet. For several years around perihelion Pluto has a tenuous atmosphere, which will eventually collapse as it moves outside the orbit of Neptune. By 2020 it is expected that Pluto's atmosphere will have largely condensed. Because of the temporary nature of its atmosphere and the fact that Pluto has yet to be explored, a flyby mission to Pluto appears attractive.

Pluto is somewhat smaller than Earth's moon (the radius of Pluto is 1150 km compared with the moon's radius of 1740 km) and itself has a moon Charon about half of the diameter of Pluto. From Earth based observations [1], it appears that Neptune's moon Triton is our best model for l'lute, while Charon most closely resembles the Uranian moon Ariel. The semimajor axis of Charon's orbit is 19640 km and Charon orbits Pluto every 6,4 days, the same as Pluto's rotation period.

Pluto is believed to be 70% rock and approximately 30% water ice with a thin methane ice surface. Its color is expected to be pinker than Triton, but not as red as Mars. Pluto also has dark mare-sized surface markings. Charon apparently only has a water ice surface.

3 SOME PAST PROPOSALS FOR MISSIONS TO PLUTO

Several missions have been proposed to Pluto in the past. The original scenarios for a Grand Tour [2] of the outer planets called for a flyby of]'lute, and more recently, studies done at Jet l'repulsion laboratory in 1990 and 1992 examined flyby missions lasting 14 years with 500 kg spat.ccraft. Lawrence Livermore National Laboratory recently proposed a 30 kg flyby spacecraft relying on high energy density batteries and a small solar array for a spacecraft that would be quiescent during most of its 5 year mission.

Most of the spacecraft proposed for Pluto flybys have been three axis stabilized [3]; however, a modification to the spinning Pioneer spacecraft had been proposed for a Grand Tour including a flyby of Pluto [4].

4 MISSION SCENARIO AND CONSTRAINTS

Mass, cost, schedule and performance, approximately in that order, drove the mission, spacecraft, as well as the attitude control subsystem design. Indeed, the original design goal called for a 35 kg spacecraft to make a fast flyby Of Pluto. It soon became obvious that a more massive version of the spacecraft, including redundancy, would be necessary to meet the mission goals within a constrained budget. Cost and schedule will be mentioned briefly again in the conclusion.

The present mission scenario to Plute) calls for at least a 6.5 year, but no greater than 8.5 year direct trajectory to Pluto with a flyby at a relative speed to the planet of approximately 15 km/s. See Figure 1. Six months prior to closest approach visible images from the Pluto Fast Flyby spacecraft will begin to be superior to those from the Hubble Space Telescope. During approach , both sides of Pluto will be imaged; however, the detailed mosaic done about an hour and a. half prior to closest approach will only be of one side, while detailed images of the other side will be made during the flyby of tile second spacecraft. See Figure '2.

Only four science instruments will be on board the spacecraft for the flyby: visible imaging, infrared and ultraviolet spectrometry cameras, as well as a radio science experiment. The visible CCD camera has a. 750 mm focal length, a 75 mm aperture, with a 1024 x 1024 array of 7.5 μm pixels giving a 10 μrad resolution. Exposure time will be about one second. A secondary objective of the mission is to do satellite searches of Plute, which might require 15 second exposures. The infrared spectrometer will use the same fore optics as the visible imaging camera and will have a 256 x 256, 40 μm pixel NICMOS HgCdTe array. Exposures may be as long as five seconds. The ultraviolet spectrometer will be a separate instrument working in. the 55 - 200 nm wavelength range. The radio science experiment will make use of an ultra- stable oscillator incorporated into the telecommunications subsystem.

The imaging data near the time of closest approach will at a minimum include a 3 x 3 mosaic of Plute, a 2 x 2 mosaic of Charon and one image, possibly near the terminator, of Pluto at closest approach. Closest approach could range from 15,000 km to as near as 5000 km above Pluto's surface, The angular separation between Pluto and Charon at the completion of the Charon mosaic an hour before closest approach will be about 6.8 degrees for a 5000 km closest approach. One way light time at the Pluto encounter will be about four hours. During the year following closest approach, the stored science data from much of the encounter will be sent back at a rate of 40 bits per second.

The change in velocity (AV) required to be executed by the spacecraft during the cruise phase of the mission will be highly dependent on the accuracy of the final solid rocket motor injection burns soon after separation from the Titan IV-Centaur launch vehicle. The Star48B and Star 27 solid rocket motors have been baselined as the upper stages. (The Russian Proton is still an option for launch). For planning purposes, the first trajectory correction maneuver will be 125 m/s on day 20 (lasting no longer than 40 minutes including time needed for off-pulsing of the AV thrusters) with the second trajectory correction maneuver of 125 m/s occurring within 10 days of that. The remaining 100 m/s will be expended over the course of the mission, with the final trajectory correction maneuver occurring 5 clays prior to Pluto closest approach. Otherwise, the cruise period will be relatively quiescent with spacecraft to Earth communications once pcr week for eight hours.

The near encounter period with Pluto and its moon Charon will only last a fcw hours during which most of the visible and infrared images will be taken. A maximum]inc of sight angular- velocity of 0.153 deg/sec is expected for a closest approach of 5000 km to the planet. Ultraviolet spectrometry and radio wave and Sun occultations by Pluto's atmosphere will also be conducted during this phase of the mission. The goal is to have imaging quality at the Pluto flyby match that met by the Voyager 2 spacecraft during

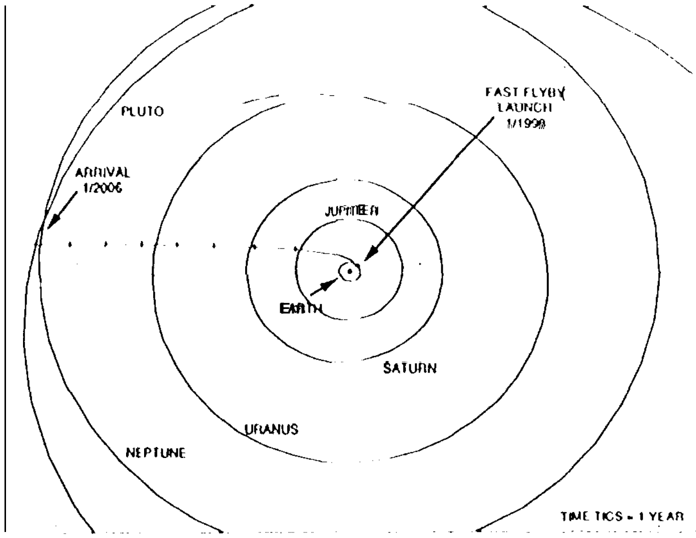

Figure 1: Direct trajectory to Pluto

its 1989 Neptune encounter.

5 THE SPACECRAFT

Given the desired pointing requirements, to be described below, a three axis stabilized spacecraft appears to be the desired option [5]. A momentum bias or dual spin spacecraft is too complicated, while a spinning spacecraft with scanners would not adequately meet the science needs of the mission and not be able to execute the quick sequence of maneuvers required for a fast flyby of the planet. The Pluto Fast Flyby has been classified as a Class C mission with selected upgrades to ensure successful completion of a potentially 10 year mission. See Figure 3. The wet mass of the present spacecraft design stands at just over 164 kg. Judicious application of low mass advanced technology may drive the mass closer to 120 kg. See [6, 7, 8, 9] for more details on the evolution and status of the present spacecraft design.

The spacecraft components will be designed to withstand radiation with a total ionizing dose of 17 kRad (Si) over a 10 year mission. For thermal reasons, near 1 AU the spacecraft is expected to point the antenna toward the sun. Spacecraft attitudes perpendicular to the sun would be limited to no more than 15 - 20 minutes. Somewhere along the trajectory between Jupiter and Saturn, pointing will begin to be unaffected by solar thermal concerns.

G ATTITUDE CONTROL REQUIREMENTS AND DESIGN

Four of the Pluto Fast Flyby operational modes give four different attitude control requirements. All requirements will be 3σ values unless stated otherwise. The trajectory correction maneuvers require that

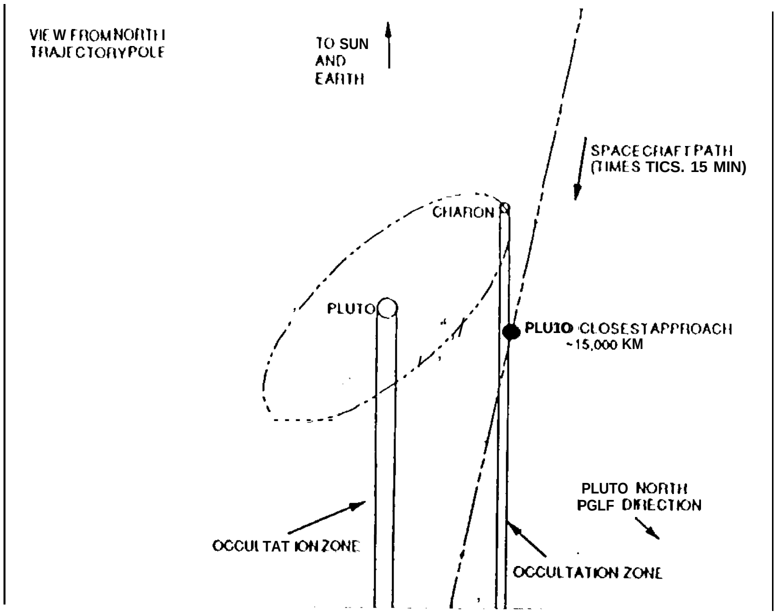

Figure 2: Pluto-Charon encounter sequence

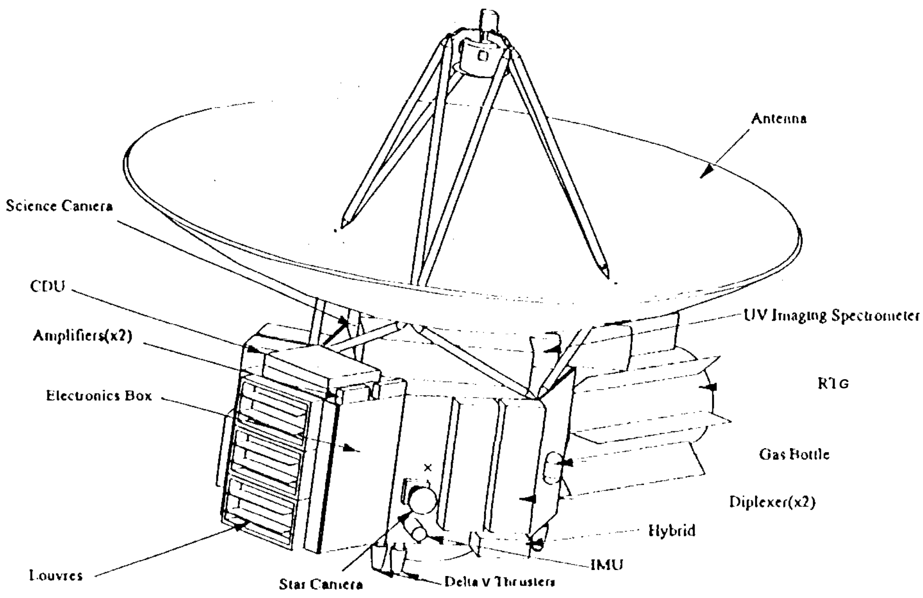

Figure 3: Pluto Fast Flyby spacecraft

the net pointing error be no greater than 36 mrad for a burn. During cruise, a pointing deadband Of at least ±2.5 degrees is imposed on the spacecraft to ensure that commands can be uplinked at any time. The downlink 011 the X-band 1.5 In parabolic antenna requires pointing control within 4.36 mrad.

The most critical pointing requirements will of course occur during the fast fly by of Pluto and Charon. The goal is to match the pointing knowledge and control capabilities met by Voyager 2 in its most difficult axis during the Neptune flyby. This will mean 1.5 mrad pointing knowledge and 2.5 mrad pointing control (2.0 mrad appears to be achievable and so will be taken as the requirement) and a peak to peak stability requirement of 10 μrad over 1 second. The pointing requirements for various phases of the mission are listed in 'J'able 1.

Because of the low mass and inertia of the spacecraft, control will need to be done with precision reaction wheels, or thrusters with very small impulse bits. A lower bound for the smallest moment of inertia about any axis at the time of closest approach is 5 $kgm2$ Because of the power needs of reaction wheels and the extra complication they provide because of their mechanical and electrical nature, it was desirable to find reaction control thrusters that could be used for attitude control.

Cold gas (gaseous N_2) thrusters do exist with a small enough impulse bit to meet the peak to peak stability requirement with a 0.2 m to 0.25 m moment arm. These thrusters have a thrust of 0.01 N and can be on for as short as 0.01 seconds, giving an impulse bit of 1 x 10^{-4} Ns. The maximum turn rate for a 90 deg turn will be about 3 minutes. The moments of inertia and thruster impulse bits of the Pluto Fast Flyby spacecraft arc about two orders of magnitude smaller than those of the Voyager spacecraft. Note that the Voyager spacecraft also had a scan platform that was used for image mosaicing; however, the most successful image motion compensation on Voyager was done with the thrusters and not its scan platform.

In order to meet the stability control requirements during the mosaics of Pluto and Charon, good models of both the inertias of the spacecraft, and the thruster impulse bits will be required. These models will dictate the thruster firing pattern while not. using a possibly noisy gyro which might disrupt the smooth imaging. The settling time required at the end of a slew is uncertain at this time; however, with no booms on the spacecraft and a low amount of fuel at the time of the encounter, the settling time is expected to be around one minute.

Because of a high leak rate specified on the cold gas system, a cold gas bottle may also be required to replenish the N_2 in the propellant tank. A total of 16 - 24 cold gas thrusters will be used on the spacecraft, including some larger ones for roll control during the trajectory correction maneuvers. Three 4.45 N hydrazine thrusters will be used to impart the AV, with three backup thrusters giving a total of six hydrazine thrusters on the spacecraft. Thrust vector control during trajectory correction maneuvers will be provided by off-pulsing of the hydrazine thrusters.

7 ATTITUDE DETERMINATION

Because of the severe mass constraints for the Pluto Fast Flyby mission, it was imperative to have as low a mass attitude determination system as possible. Therefore, it was obvious that an Inertial Reference

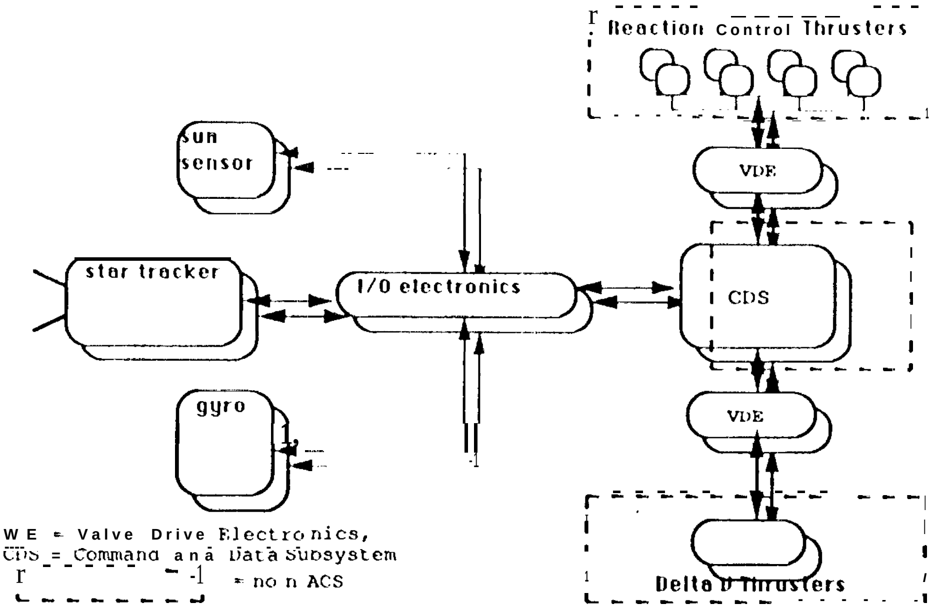

Figure 4: Attitude control subsystem block diagram

ACS requirement	value
ΔV pointing error	36 mrad
Deadband pointing	±2.5 deg
X-band downlink	4.36 mrad
imaging attitude knowledge	1.5 mrad
peak to peak stability	10.0 μrad over 1 sec.
imaging attitude control	2.0 mrad

Table 1: Attitude control subsystem (ACS) requirements for various phases of the mission.

Components	Mass (kg)	Power (each, watts)
star tracker (2)	0.60	3.[illegible]
IRU (2, 3 axis)	0.40	6.1
sun sensor (2)	0.20	0.05
valve drive electronics (2)	1.0	0.5
I/O electronics (2)	0.5	1.0
Total	2.7	11.4.5

Table 2: Mass and power goals for ACS components

Unit (IRU) like the Fiber Optic Rotation System proposed for a Pluto study in 1990 with a mass of 10 kg was not a viable option.

Indeed, if a low mass IRU was called for, it also meant that it would most certainly be substantially below navigation grade. This implied that most of the attitude determination burden would have to be placed on the star tracker. It also implied that the spacecraft could not be propagating attitude on an IRU for long without incurring large errors. In addition, the short time of the flyby sequence of mosaics and occultations requiring quick turn maneuvers precludes being able to turn to the sun and a star for an attitude update as was done on Voyager (and took up to 20 minutes). The lack of a scan platform also precludes keeping on sun and a star while simultaneously doing science. All of these factors led to the desire for an all-sky star tracker which could be pointed at any point in the celestial sphere, and in a matter of a few seconds, but no more than a minute be able to determine the spacecraft's attitude.

A 1.5+ MIPS central computer resource with 1+ M byte processor memory will be available for the star identification and attitude calculation.

8 HARDWARE AND SOFTWARE FUNCTIONS

In this section we present some of the hardware requirements for the star and feature tracker, the Inertial Reference Unit and the sun sensor for the Pluto Fast Flyby attitude control subsystem. We also briefly mention some of the functions of the valve drive electronics and input/output (I/O) electronics. Some of the algorithms to be included in the ACS software are listed, A block diagram of the attitude control subsystem is shown in Figure 4. We summarize in Table 2 mass and power estimates of possible hardware for the attitude control subsystem. The table does not include the mass estimate for any cables or connectors.

8.1 STAR AND FEATURE TRACKER

The star tracker obtains star data to support attitude determination functions, sometimes in conjunction with the IRU. Two trackers will be flown on the spacecraft with one as a redundant spare. The accuracy of measured star centroids shall be less than or equal to 200 $\mu rad (1\sigma)$ for spacecraft roll rates less than 0.3 deg/sec. The tracker shall have a mass less than .500 grams and consume 5 watts maximum power at +15 VDC. It should also be able to survive 15 minutes exposure to the sun anywhere in the field of view. The tracker may also be used for feature tracking at Pluto closest approach.

An important concern to be addressed for the emerging miniature star trackers, some of which are wide field of view with fiber optic field flatteners, is their ability to operate continuously for a 10 year mission. The possibility of using the tracker as a sun sensor also exists if integration times can be made short enough.

8.2 INERTIA 1, REFERENCE UNIT

The Inertial Reference Unit (IRU) is not expected to be on for more than 1000 hours during the entire mission. A particularly attractive option for the IRU appears to be the Lightweight Attitude Reference Unit (LARU) based on Honeywell's GG1308 Ring Laser Gyro. This unit has a mass of 208 grams, power input of 6.1 watts and can tolerate a maximum input rate of 2000 deg/sec. The bias stability is 2.9 deg/hour (1 σ) after 16 hours of temperature variation, and has a rate white noise power spectra] density of 1.2 x 10^{-9} rad^2/sec. Life issues to be addressed include outgassing and mirror pitting.

8.3 SUN SENSOR

A sun sensor could be used in both locating the direction of the Earth during an emergency and helping to determine the spacecraft inert.ia.l orientation in two axes. Mass and power goals for the sun sensor are listed in Table 2. The sun acquisition field of view is $\pm$ 30 deg, with the control field of view being $\pm$10 deg and a control accuracy of $\pm$ 0.5 deg. The sensor will need to be operable out to 35 AU.

8.4 VALVE DRIVE ELECTRONICS AND INPUT-OUTPUT ELECTRONICS

Few details have been worked out for the valve drive electronics or 1/0 electronics designs. The valve drive electronics are to provide control for the thruster valves and heaters while at the same time providing electronic isolation against stray signals, The 1/0 electronics shall, among other tasks, send and interpret messages, interpret commands, send commands and provide for a delay of command execution.

8.5 SOFTWARE FUNCTIONS

The flight software is most likely to be written in the C programming language and will operate in the central computer resource. Some of the ACS algorithms to be executed in the computer include:

- Sun search
- Sun acquisition

- star pattern identification
- star centroid calculation
- attitude quaternion calculation
- inertial attitude propagation
- attitude correction within deadband
- target motion compensation
- off-pulsing attitude stabilization for trajectory correction maneuvers
- fault management
- spacecraft turns
- IRU calibration
- Sun sensor calibration
- star tracker calibration

9 CONCLUSION

The Pluto Fast Flyby study is proceeding at an ever rapid pace with the goal of launching a small spacecraft to Pluto before the decade is over. A technology freeze will occur in April 1995 with the new start slated for October 1995. A launch as early as February 1998 is contemplated with launches possible every February in succeeding years. The goal for the project is to control costs through launch +- 30 days to less than FY92 $400 million.

The present spacecraft design baseline is being modified with refinements in the design, and advanced technology insertion in selected areas to reduce the total mass of the spacecraft to 120 kg from 164 kg.

This paper presented the conceptual attitude control subsystem design for the Pluto Fast Flyby spacecraft. That design has responded to the desire to minimize the mass and cost while presenting viable options to meet the stringent demands for a fast flyby of one of our outermost planets.

ACKNOWLEDGMENT

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